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DETERMINATION OF POTENTIAL SOLAR POWER SITES IN THE UNITED STATES BASED UPON SATELLITE CLOUD OBSERVATIONS

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16. Abstract Ground measurements of solar radiation are too sparse to determine important mesoscale differences that can be of major significance in solar power station location. A method is presented for use of cloud images in the visual spectrum from the SMS/GOES geostationary satellites to determine the hourly distribution of sunshine on a mesoscale in the continental United States excluding Alaska. Cloud coverage and density as a function of time of day and season are evaluated through the use of digital data processing techniques. Low density cirrus clouds are less detrimental to solar energy collection than other types; and clouds in the morning and evening are less detrimental than those during midday hours of maximum insolation.

Seasonal geographic distributions of cloud cover/sunshine are converted to Langleys of solar radiation received at the earth's surface through relationships developed from long-term measurements of these two paramters at six widely distributed stations. The technique ultimately can be used to generate maps showing the geographic distribution of total solar radiation on the mesoscale which is received at the earth's surface.

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PREFACE

The objective of this research is to demonstrate a technique for using the SMS/GOES geostationary satellite cloud imagery data to monitor the seasonal and mesoscale geographic distribution of solar energy reaching the earth's surface in the 48 contiguous United States and nearby waters in order to determine optimum locations for solar power stations. By monitoring daytime cloud cover every half hour, a geostationary satellite can determine the temporal distributions of sunshine received at a given place or in a small geographic area.

Many researchers have found good relationships between the duration of sunshine and gram calories of solar radiation received at a given place for a specified period of time. Several ground-truth stations at different latitudes and climates have sunshine and solar radiation recorders co-located and cloud observations are made at most of these stations. Data from these are used to obtain the required transform equations for converting satellite measurements of clouds/sunshine to solar energy received at the earth's surface.

Data from the eastern SMS/GOES geostationary satellite at 75 degrees West longitude over the equator has been used for this project. Data from the western SMS/GOES at 135 degrees West provide better resolution over the northwestern states, but data processing is more complex when two satellites are used. Unfortunately, most original digital tapes of data from these satellites have been erased. The best available archive is in the form of 10 x 10-inch photo transparencies. It is necessary to read these with a digital densitometer or a TV scanner such as the GE Image 100 in order to digitally process the data. In the future, original tapes could be stored and analyzed to avoid the photo process.

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1.0 INTRODUCTION

Intermediate scale (mesoscale) differences in the distribution of solar radiation received at the earth's surface can be very important in selecting the location for a large solar energy station. Daily totals and in some cases hourly records of solar insolation exist for about 54 National Weather Service and 27 Cooperative stations in the 48 contiguous United States [1]. A popular belief is that the distribution of solar radiation in the United States is already known. Figure 1 is a map of mean daily solar radiation on an annual basis [2]. This is based upon data from a small number of recording stations. There are many areas within this pattern that are much better or much worse solar energy sites than indicated by the map. The geostationary satellites, providing half-hourly cloud observations with space resolution on the order of 2-4 kilometers in the United States, permit us to determine those localized differences in solar radiation received at the earth's surface. This can prevent serious mistakes that might otherwise be made in locating major solar power stations based upon the existing sparse network of recordings. Lakes, bays, swamps, hills, irregular coastlines, etc. can all play major roles in the temporal and space distributions of clouds.

Since clouds of the "low-cloud family," including those of vertical development, tend to be thick and contain lots of moisture, they are the major absorbers or attenuators of incoming solar radiation. These low cloud types are most responsive to surface features such as localized heating or cooling, coastal effects, and topography. This responsiveness is manifest in the time, space, and density distributions of these low cloud types. These localized differences in the low-cloud family are the major cause of mesoscale differences in solar radiation reaching the earth.

There are two types of solar radiation measurements commonly made at the earth's surface, direct and global. Direct is that received directly from the sun and is measured on a flat surface normal to the sun's rays. The Eppley normal incidence pyrheliometer is a typical instrument used for this. Global radiation is the direct plus that reflected from all parts of the sky, and it is measured on a horizontal flat surface. The Eppley model II pyranometer is a typical instrument for this measurement. At

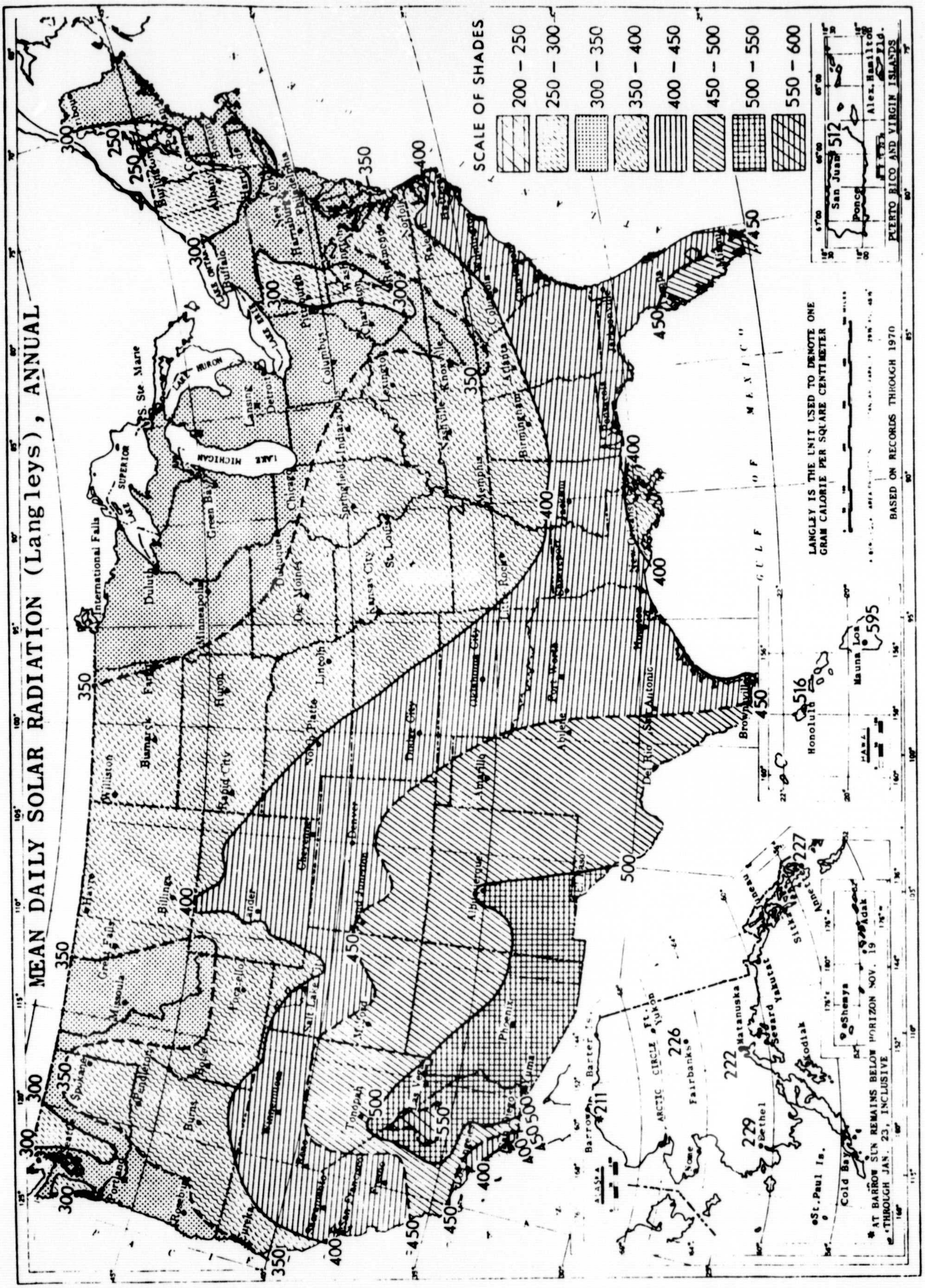

Figure 1 Mean Daily Solar Radiation, Annual for United States

many stations, daily totalizers are used on both types of instruments. At some stations, analog chart recorders are used so that the time distribution and hourly totals of radiation can be obtained, [1]. Eighteen of the National Weather Service pyranometer stations that have analog chart recorders, which provide hourly radiation data, also have sunshine switches with recorders that provide minutes of sunshine per hour, and cloud observations are made at most of these stations. The sunshine switches are calibrated to indicate sunshine so long as enough sunlight is present for nearby objects to cast a shadow. Thus periods with high thin clouds are recorded as sunshine. Depending upon the threshold of the switch, heavier clouds may also register as sunshine.

In this study, global solar radiation received per hour is correlated with minutes of sunshine and opaque cloud cover per hour recorded at 6 surface stations in different climatic and air quality regions of the United States. The SMS/GOES geostationary satellites provide mesoscale images of cloud cover and conversely sunshine by hours of the day. The ground station relations between clouds/sunshine and total radiation are used to transform the satellite measurements of sunshine into equivalent solar radiation data. Computer processing of the data provides seasonal mapping of sunshine and solar radiation on the mesoscale, Hiser and Senn [3], [4]. Early research on the use of satellites to measure solar energy was conducted by Fritz, et al. [5]. More recent works relating to the subject include Thekaekara [6], Hanson [7], and Vonder Haar [8].

In addition to cloudiness, latitude, season of the year, time of day, and air quality (turbidity, etc.) are important factors in solar insolation. Cloudiness with respect to time of day is important because morning and evening cloudiness is less detrimental than that at midday. This can be particularly important if a high temperature solar concentrator is to be used, in which case, the midday high energy hours of sunshine would be most valuable. The geostationary satellite observations throughout the day provide these hourly distributions of cloudiness and sunshine.

Surface data used to write the transforms from clouds/sunshine to solar radiation are from 6 stations throughout the United States. For example, Great Falls, Montana, data applies to the northern high plains and data for El Paso, Texas applies to the dry southern regions. This system automatically compensates for differences in air quality because each station is fairly representative of its region.

2.0 RELATIONS BETWEEN SUNSHINE, CLOUD COVER, AND SOLAR RADIATION AT THE EARTH'S SURFACE

2.1 Introduction

The data were obtained from the National Climatic Center on three 9-track, 1600 bpi tapes containing hourly radiation data from Card Deck 280 for the locations shown in Table 1. An attempt was made to obtain complete data for a continuous 5-year period, 7/52 - 6/57 from each station. Due to lack of time, six stations were chosen for analysis on the basis of geographical representation, completeness of records, and/or the existence of other comparison data. These are Hatteras, NC; Madison, WI; Sault Ste. Marie, MI; El Paso, TX; Great Falls, MT; and Fresno, CA.

The "Deck 280-Solar Radiation-Hourly Record" data extracted consisted of "Sunshine" (0-60 min., col. 23-24), "Opaque Sky Cover" (0-10 tenths, col. 36) and "Radiation-Langleys per Hour" (col. 14-17). "True Solar Time" (TST) (00-23 hrs., col. 38-39) was the beginning of the hour of data represented. See Figure 2. Data were computed and plotted for each hour of the day. But, as will be shown later, great variations are almost always present in one or more of the variables when the number of observations is very low. In such cases they tend to be unrepresentative of a given situation. In order to correct for that, hours at the beginning and end of the day and throughout the day with equal sun angles were combined in some of the analyses so that there would be more data making up each point on the graph.

Computer programs were written to compute the radiation in Langleys per hour for each of sixteen hours averaged over the five-year period for 30 days simulating typical months for four representative seasons centered on the equinoxes and the June and December minimum and maximum solar declination angles. This was done to determine whether significant variations in the relationships between skycover and radiation and/or sunshine and radiation were present on a seasonal basis. If zero Langleys of radiation were recorded during the hours of 0800-1600 in March and September, 0700-1700 in June, and 0900-1500 in December, that observation was deleted regardless of the skycover or sunshine which may have been recorded during the same hour. This was done on the basis that during the daylight hours one or two hours after sunrise until an hour

DECK 280 SOLAR RADIATION - HOURLY RECORD

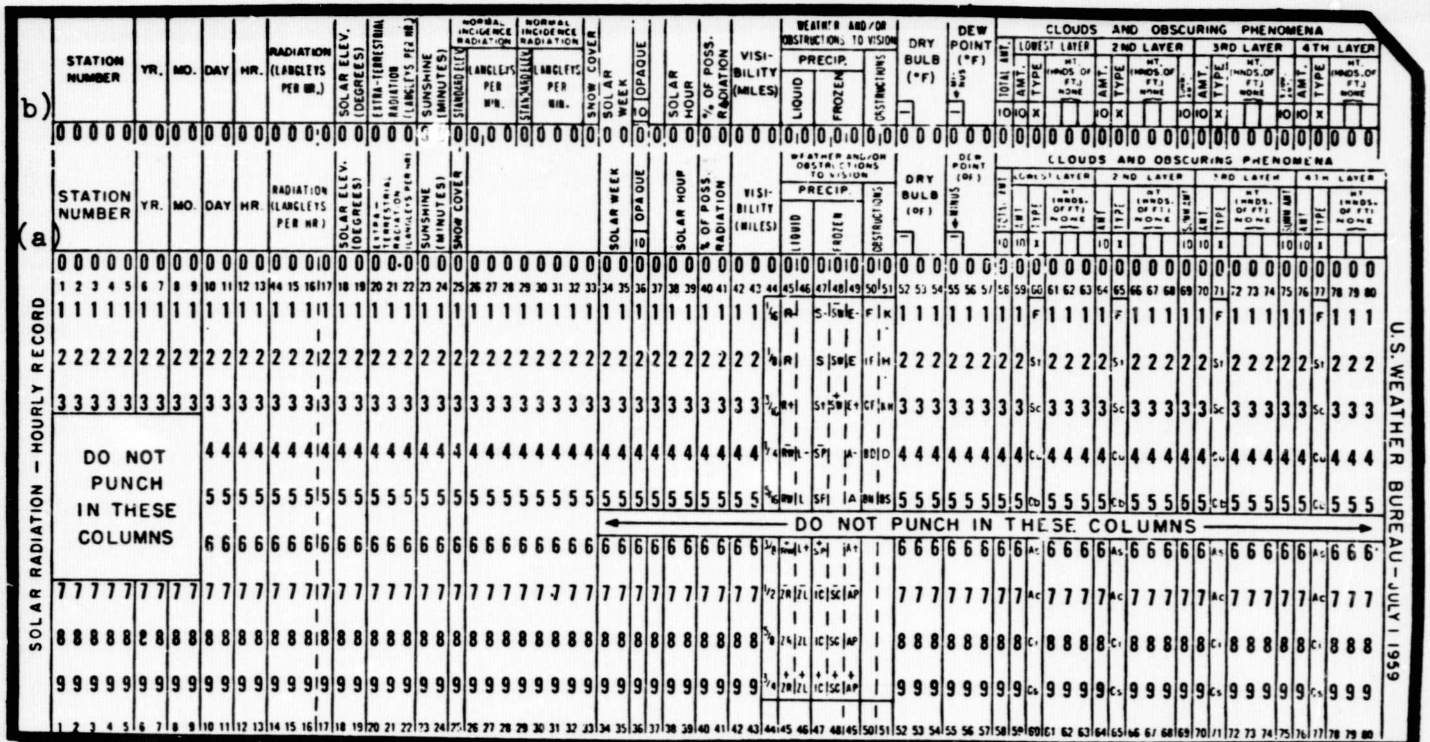

Figure 2 Deck 280 Solar Radiation - Hourly Record

TABLE 1 SOLAR RADIATION DATA

NATIONAL CLIMATIC CENTER, ON TAPE

Reel #	Station #	Name	Period	Missing Data
1	12832	Apalachicola, FL	7/52-6/57	6-8/53, 2-3,7-12/54
	12919	Brownsville, TX	7/52-6/57	7,12/56, 1-2/57
	13745	Hatteras, NC	7/52-2/57	
	13897	Nashville, TN	7/52-6/57	8-9/53
	13893	Columbia, MO	7/52-6/57	
	13985	Dodge City, KS	7/52-6/57	
	14820	Cleveland, OH	7/52-7/53	1/53
	14837	*Madison, WI	7/52-6/57	
1&2	14847	*Sault Ste. Marie, MI	7/52-6/57	
	14939	Lincoln, NE	8/52-8/55	
	23044	*El Paso, TX	7/52-6/57	
	23050	Albuquerque, NM	7/52-6/57	
	23154	Ely, NV	7/52-6/57	
	24011	Bismarck, ND	7/52-6/57	
	24143	*Great Falls, MT	7/52-6/57	
	93193	*Fresno, CA	7/52-6/57	
	93729	*Cape Hatteras, NC	3/57-6/57	
2&3	94701	Boston, MA	7/52-6/57	10-12/53, 12/54
	94706	New York/Central Park	7/52-6/57	

* stations analyzed

or two before sunset, even with full sky cover at least a fraction of a Langley would normally be received. If it was not, there probably was a problem with the data somewhere along the line, so it was discarded. This resulted in the loss of about 5-10 observations out of 150 for a given hour of a given month.

The same programs were used to compute the hourly sky cover in tenths of sky covered by clouds, and slightly modified for different categories of sunshine in minutes per hour. Samples of the data were plotted against each other to determine the relationships which exist and how the data could be combined to portray the climatology of each station for later correlation with the satellite cloud cover data.

Hanson, [7], Quinn, [9], and others have attempted to parameterize solar radiance at the earth's surface by means of cloudiness observed there and from satellites. They found that both the type and the amount of clouds as well as the length of records were important factors necessary to reducing the undesirable variations in radiation. However, this research is not so interested in achieving accurate absolute values of solar radiation at a given point by use of satellite cloud data as to illustrate the very important mesoscale differences in energy received on a comparative basis within a given region. Once the relative patterns are determined, ground truth solar radiation measurements can be used for absolute calibration of the results.

With that in mind, our research program efforts were directed toward: a) the goal of establishing whether the same general relationships between global radiation and either sky cover or minutes of sunshine at one station would be found at others of widely varying latitudes or climate; b) by finding the parameter (sky cover or sunshine minutes) which is routinely measured at a number of United States stations along with radiation, which correlated with it and which could most realistically be used to correlate with our final product, the visual satellite photograph; and c) to set up the procedures and software programs which could be used for actually producing data for any point in the United States.

2.2 General Data Characteristics

2.21 Radiation

Figure 3 shows radiation versus time of day for each month and the yearly average for four of the six stations. The general latitudinal variations one might expect to find are apparent, with Fresno and El Paso receiving much more radiation during every season than higher latitude stations such as Great Falls and Sault Ste. Marie. Despite the near similarity in sun angle in March and September, some of the stations receive more radiation in March than September (El Paso, Hatteras, and Sault Ste. Marie), while Fresno and Madison show the reverse. The differences are greatest during the middle of the day. The data were also plotted for the calendar months of March and September, and the greater differences due to the slightly lower sun angles for more days in March were immediately apparent.

More important is the fact that while March and September radiation are roughly double the December radiation, the maximum June radiation is only about 35% higher than the average of March and September. The June increase in radiation is in reasonable compliance with the decrease in the cosine of the sun's zenith angle but neglects the almost equal percentage (28%) of additional hours of radiation available in June. The December departure from March and September is 50% greater than the June difference, largely accounting for both the change in zenith angle and the greatly reduced (about 60%) number of hours of available radiation.

Although there have been problems with the black absorption coating on the pyranometers used to gather radiation data in the past, Flowers [10], the five-year period chosen seems to have been relatively free of spurious influences. Compared to the sunshine and cloudiness data the radiation data are more consistent and less subject to large unexplained deviations, especially as longer period averages are used.

It is important to remember that the radiation data are the basis for the future decisions on the siting of solar power plants; but that they are simply unavailable for well over 99% of the United States on the mesoscale. Consequently, the vagaries of other data, such as sky cover and possibly sunshine, must be investigated as indicators of solar energy received at a given location.

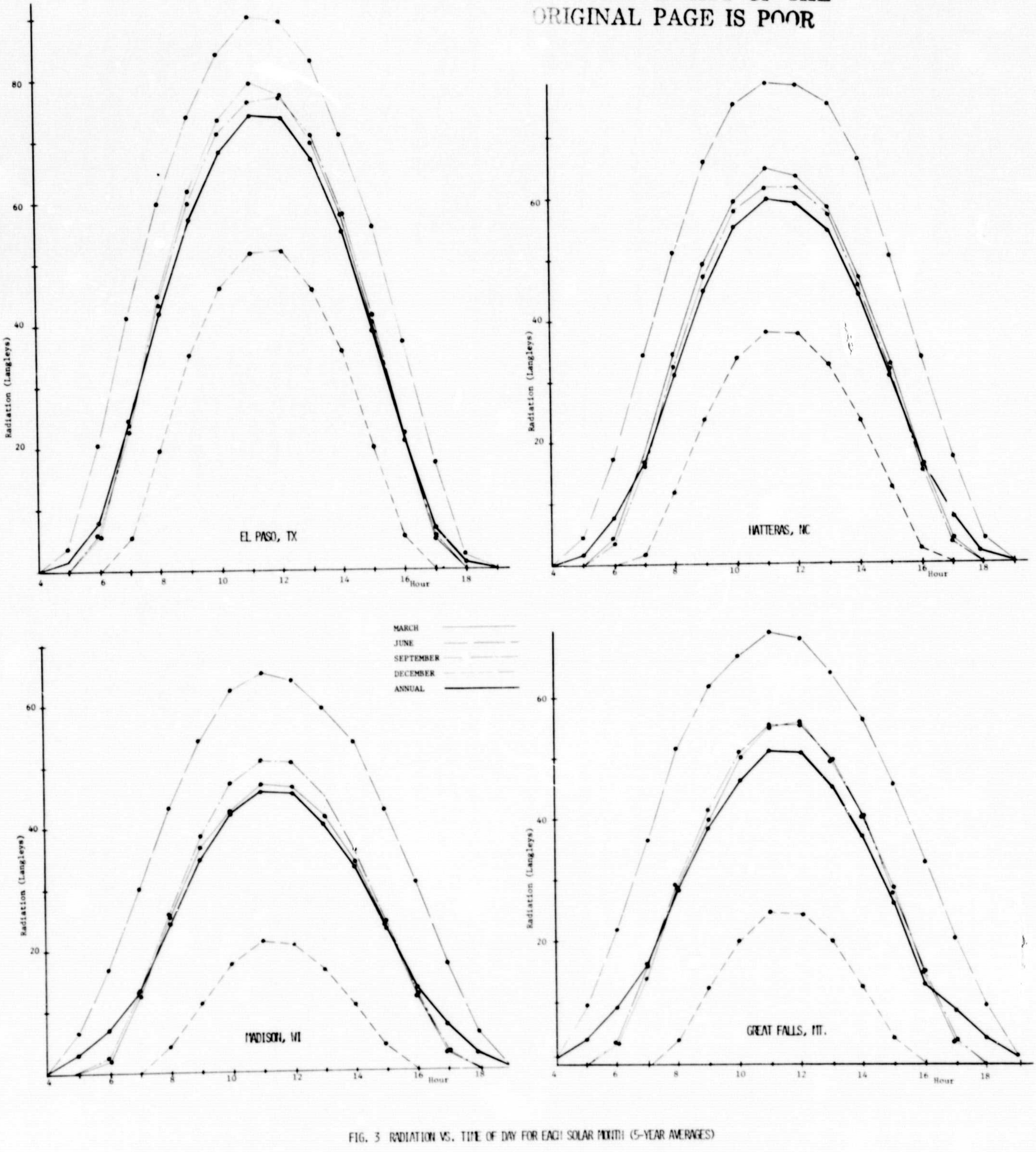

FIG. 3 RADIATION VS. TIME OF DAY FOR EACH SOLAR MONTH (5-YEAR AVERAGES)

2.22 Sunshine

Minutes of sunshine are recorded by the National Weather Service (NWS) with an instrument known as the "photoelectric sunshine switch," which maintains its calibration reasonably well, but does not yield very useful short-term data for studies such as these, even though others have found good correlations between hours of sunshine and radiation received at a given place. (References [11], [12], [13], [14], [15], and [16]). However, the threshold of the present NWS switch is set to record sunshine whenever shadows are visible, a condition which can and does occur under widely varying conditions.

When there is still reasonably heavy cloudiness, the NWS sunshine recorder will often register sunshine despite almost total lack of it. However, when the sunshine switch shows no sunshine, it is certainly overcast or there is an equipment problem. Therefore, the data correlations should be best only at the completely overcast, low-radiation end of the scale. At the "clear" high-radiation end of the scale they will show a maximum scatter of points when plotted against other variables because of the great variety of conditions under which sunshine will be recorded. Since the sunshine switch is qualitative only, all points in between the end points necessarily contain a very large element of doubt and scatter.

Figure 4 illustrates for all six stations the same conclusions as shown in Figure 3, that even though the data are smoothed by including five years of records, inconsistencies are still evident. Other data were plotted on shorter time bases showing much greater problems at all points other than the overcast end points. Consequently, less was done with this variable than with radiation and skycover.

However, some interesting conclusions emerge from the hourly averages in Figure 4. The longer the period of sunshine, the flatter the curve appears in the middle of the day regardless of sky cover, shown below. That clearly indicates that the sunshine switch, erroneously records sunshine too often under cloudy conditions. Some earlier investigations of relationships between solar radiation and sunshine has data available from what appears to have been superior types of sunshine

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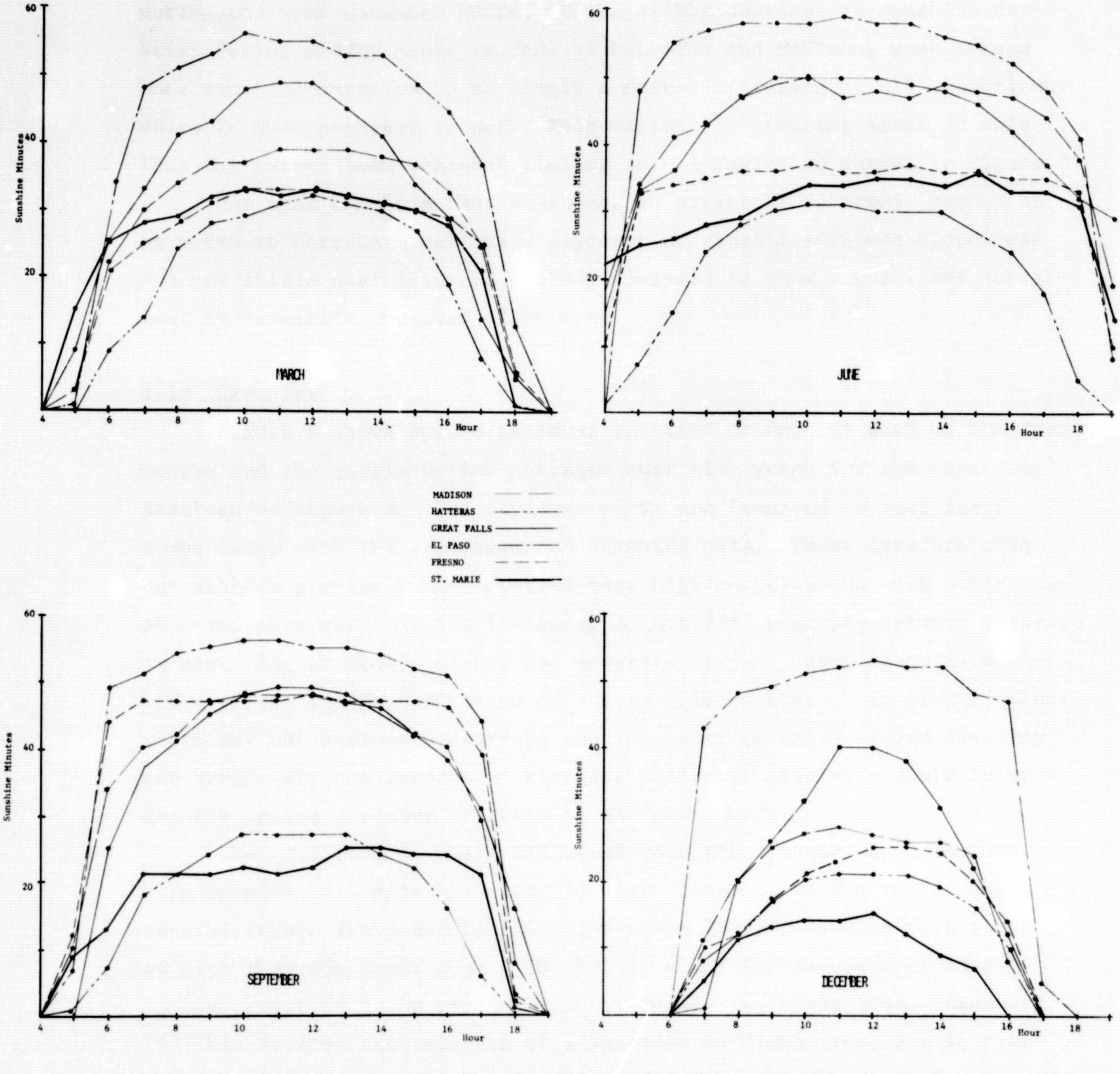


FIG. 4 SUNSHINE VS. TIME OF DAY FOR EACH SOLAR MONTH (5-YEAR AVERAGES, 6 STATIONS)

recorders. Although some of the results seem significant, such as the drop in sunshine in the afternoon hours at El Paso in June, the increase during the same December hours, or the slight decrease in sunshine duration during midday hours in June at Hatteras and Madison, most curves show sunshine duration to be simply a matter of season at all locations, which it most probably is not. This variable's greatest asset is only that the curves look somewhat similar to the radiation curves in Figure 3.

One must conclude that sunshine, as presently recorded, cannot be expected to correlate well with skycover or satellite-viewed cloudiness and has little usefulness in a study designed to show significant variations in satellite-observed cloudiness.

2.23 Skycover

Figure 5 shows opaque skycover vs. time of day for each of the four months and the yearly period averaged over five years for the same four stations as Figure 3. The skycover plots are inverted to facilitate comparisons with the radiation and sunshine data. These data are also not without problems which prevent very high correlations with other data. Skycover observations, for instance, do not differentiate between moderate to heavy low or middle clouds and moderate cirrus. Each cloud category would affect the transmittance of energy differently. Thin cirrus clouds which may not seriously decrease the intensity of solar energy reaching the ground are not recorded. However, different observers would interpret the opaque skycover criteria in different ways.

The situation is quite different with cloud cover which becomes more complex with multiple cloud layers. Under reporting rules, when several layers are present, those above the lower ones cannot be coded as less than the lower ones. The hourly total for the various layers is then reported to be greater than it really is, never less. Haurwitz, [17] has studied the relation of insolation to cloud type, but to overcome most of the above problems, he confined his study to completely overcast conditions only. Norris [18] concluded that sky cover as deduced from cloud classes was well correlated to solar energy only on a monthly or longer basis, though Lumb [19] used nine categories of clouds

and obtained good correlations with short wave radiation at the sea surface. Reddy [20] developed an empirical method for computing sunshine from total cloud amounts for water budget/energy studies. But Bennett [21] found that opaque skycover was far superior to average total skycover as an indicator of insolation received. Consequently, we have used opaque skycover instead of cloud cover.

Despite the problems with the opaque skycover data, they have less scatter and seem more reliable than the minutes of sunshine data; but they are certainly not as good as the radiation data which are not widely available.

Even more serious is the relatively low number of observations between the end points when a histogram of hours of opaque cloudiness is plotted. For Madison, a station with equal numbers of overcast (1997) and clear (1993) hours, the other nine categories (82%) of cloudiness contain only 35% of the observations. Other stations have worse ratios, some a bit better. While nature may explain part of that, part is probably due to observation problems.

Figure 5 was designed to show whether there were significant variations in skycover at different hours of the day during the four seasons at each of the four stations. El Paso, for instance has more clouds in the afternoon during all seasons but winter (December). Hatteras has more during the middle of the day only in June, possibly due to a summer sea-breeze effect. Great Falls also has a bit more skycover in the afternoons in June.

In a few instances the skycover data of Figure 5 seems to correlate with the sunshine duration data of Figure 4. For instance, the June increase in El Paso and Great Falls skycover in afternoon hours and the decrease in sunshine. However, in others, such as the decrease in midday sunshine at Madison for June, there is no corresponding result in Figure 5. And the same midday sunshine decrease in Figure 4 for Hatteras shows a decrease in skycover in Figure 5 rather than an increase.

We conclude that despite the slightly noisier characteristics of the skycover curves, they do not always portray June as the least skycovered month nor December as the most at all stations as the sunshine data would imply. Furthermore, although there are obvious problems, the

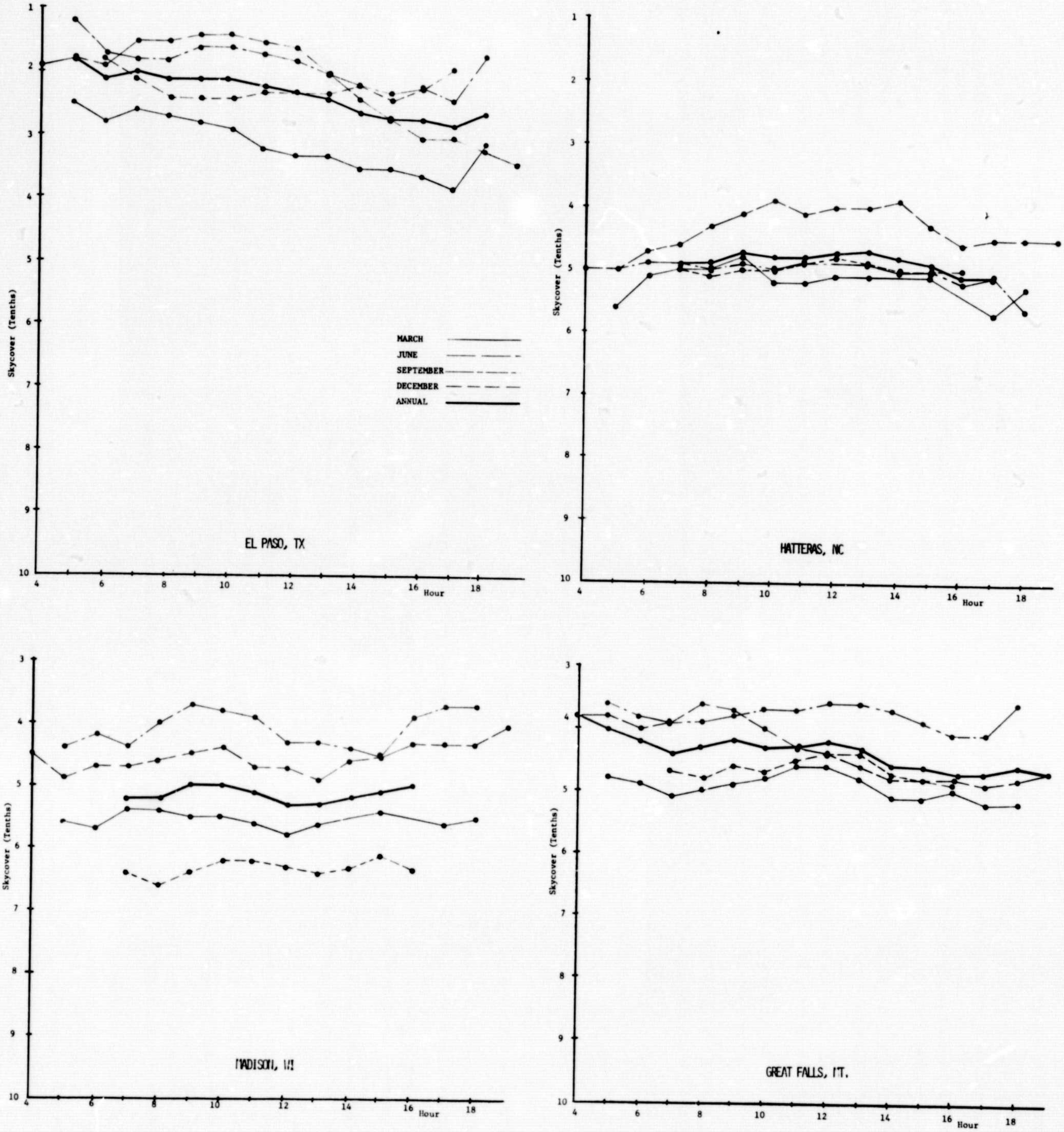


FIG. 5 SKYCOVER VS. TIME OF DAY FOR EACH SOLAR MONTH (5-YEAR AVERAGES)

methods used to observe and record the skycover are more valid and the data are therefore much more likely than sunshine data to correlate with satellite observed cloud cover.

2.3 Radiation vs. Skycover

The four solar months of data were analyzed for the five year period 1952-1957 for the six stations given above. Other plots were made on a calendar month basis for the same stations; but these were harder to analyze than those made on a solar month basis, and were discarded. Table 2 shows a list of plots which were done on the variables Radiation vs. Skycover and Radiation vs. Sunshine on a solar month basis. Not all of the graphs are included in this report.

Table 2

Plots of variables from 5-year data sample on six stations* including all four solar months on each.

	Radiation vs. Skycover	Radiation vs. Sunshine
0900 monthly and annual average	x	x
1500 monthly and annual average	x	x
Combined 0900 and 1500 only	x	x
Combined 1100 and 1200 only	x	
All-hour average monthly and annual average	x	x

* El Paso, TX; Fresno, CA; Hatteras, NC; Madison, WI; Sault Ste. Marie, MI; and Great Falls, MT.

Figure 6 shows the four monthly graphs of skycover vs. radiation, each including all six stations. All show the same general characteristics: very little decrease in radiation received with the first few tenths of skycover; very rapid decrease in radiation received with the last few tenths toward the overcast end of the skycover scale; and a generally greater departure from smooth curves when the number of

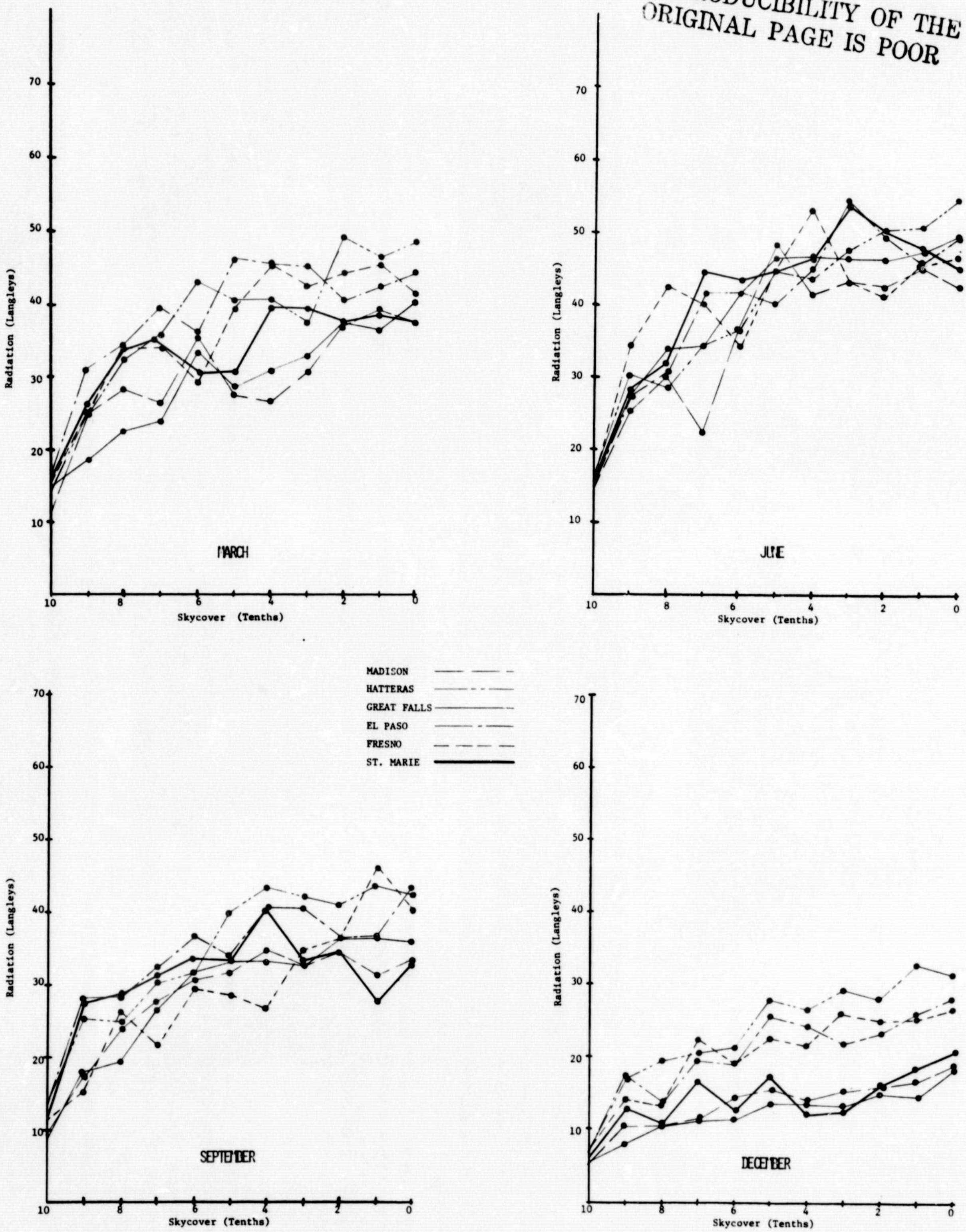


FIG. 6 RADIATION VS. SKYCOVER FOR FOUR SOLAR MONTHS (5-YEAR AVERAGES, 6 STATIONS)

observations falls below 80 or so. The shape of all the curves is similar, but the degree of curvature is greatest in June, least (flattest) in December. Another interesting and important result is that the scatter in the end points is very small at the overcast, low radiation end of the scale and relatively great at the clear sky, greatest radiation points. Also, the end points represent about an order of magnitude more data points than those between. For instance, El Paso has over 85% of all data points in the two end-point values. Consequently, they should be much more reliable. The least scatter in the centers of the graphs occurs in June when the radiation is greatest and the stations all having similar relationships; with March and December both showing more scatter and wider differences between radiation received and skycover.

The annual curves combining all four months for each station are shown in Figure 7. Their general characteristics amplify the above conclusions.

In order to look at possible differences between morning, noon and afternoon radiation or skycover, the data were plotted for 0900 for each month as well as 1100 and 1200 and for 1500. Results were generally as expected in that the radiation values are much higher during middle of the day hours during all months. But since the number of data points was greatly decreased, the scatter or deviations from the general curve shape shown in Figure 7 were greater. The other features remained similar, especially the remarkably equal radiation received for these stations under total skycover conditions.

2.4 Radiation vs. Sunshine

Table 2 lists the plots made from computer data summaries of radiation versus sunshine. The same general comments apply to these figures as to the radiation versus skycover shown above, except that these plots are a mirror image of the earlier ones. Where radiation increased dramatically from 1 to 8 tenths of skycover, it increases only slowly from 0 to 15 or 20 minutes of sunshine (each hour); where radiation almost completely leveled off from 3 to 0 tenths of skycover, it increases dramatically with 50 to 60 minutes of sunshine. These features are shown in Figure 6 for radiation versus skycover and Figure 8 for

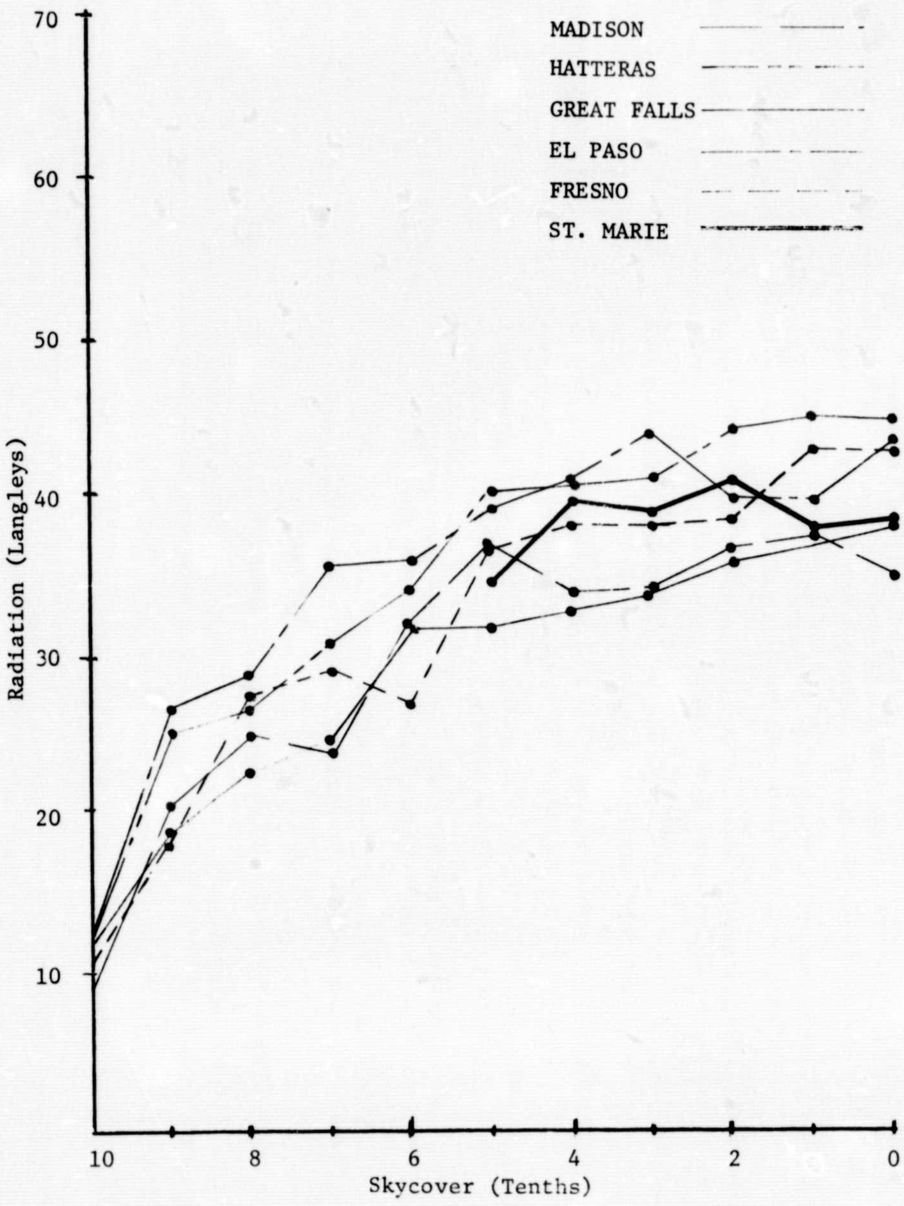


FIG. 7 RADIATION VS. SKYCOVER, ANNUAL CURVES (5-YEAR AVERAGES, 6 STATIONS)

radiation versus sunshine.

Figure 8 also shows more variations from smooth curves for the middle values of radiation and sunshine during all of the months. In the case of Fresno, the variations are so great that the data may be suspect, including the zero-minute sunshine value, despite the very great number of observations that comprise that point during some months. September and June are especially suspect at most intermediate sunshine values. Hatteras and El Paso curves have somewhat the same shapes during those same months but are not as pronounced.

The annual curves shown in Figure 9 are considerably smoothed since they contain more data than the monthly curves. However, they still are not as smooth as one would expect, showing that the vagaries of the sunshine switch are not necessarily overcome by increasing the sample size.

2.5 Relations Between Solar Energy and Cloud Cover

As indicated in paragraph 2.0, others have attempted to parameterize the relations between solar energy received at the earth's surface and cloud cover with varying degrees of success. Our data show that the problems which exist in the methods of defining and recording both "skycover" and "sunshine" may not be the same from station to station or from instrument to instrument within the recording network of the relatively few stations which gather such data.

We conclude that the recording of solar energy received which is listed as "radiation" data is far superior to the "skycover" or "sunshine" recordings; despite the general lack of breakdown between direct and diffuse components; and despite the fact that no general data are available for energy received at angles other than the horizontal at most of the recording stations. Consequently, the "radiation" data are the standards against which all other variables have been compared in this study.

Despite the imperfections in the "skycover" recordings enumerated above those data are superior to the sunshine data. Even though they are not intuitively as representative of the radiation standard as sunshine might be, they are certainly more comparable to the cloud cover

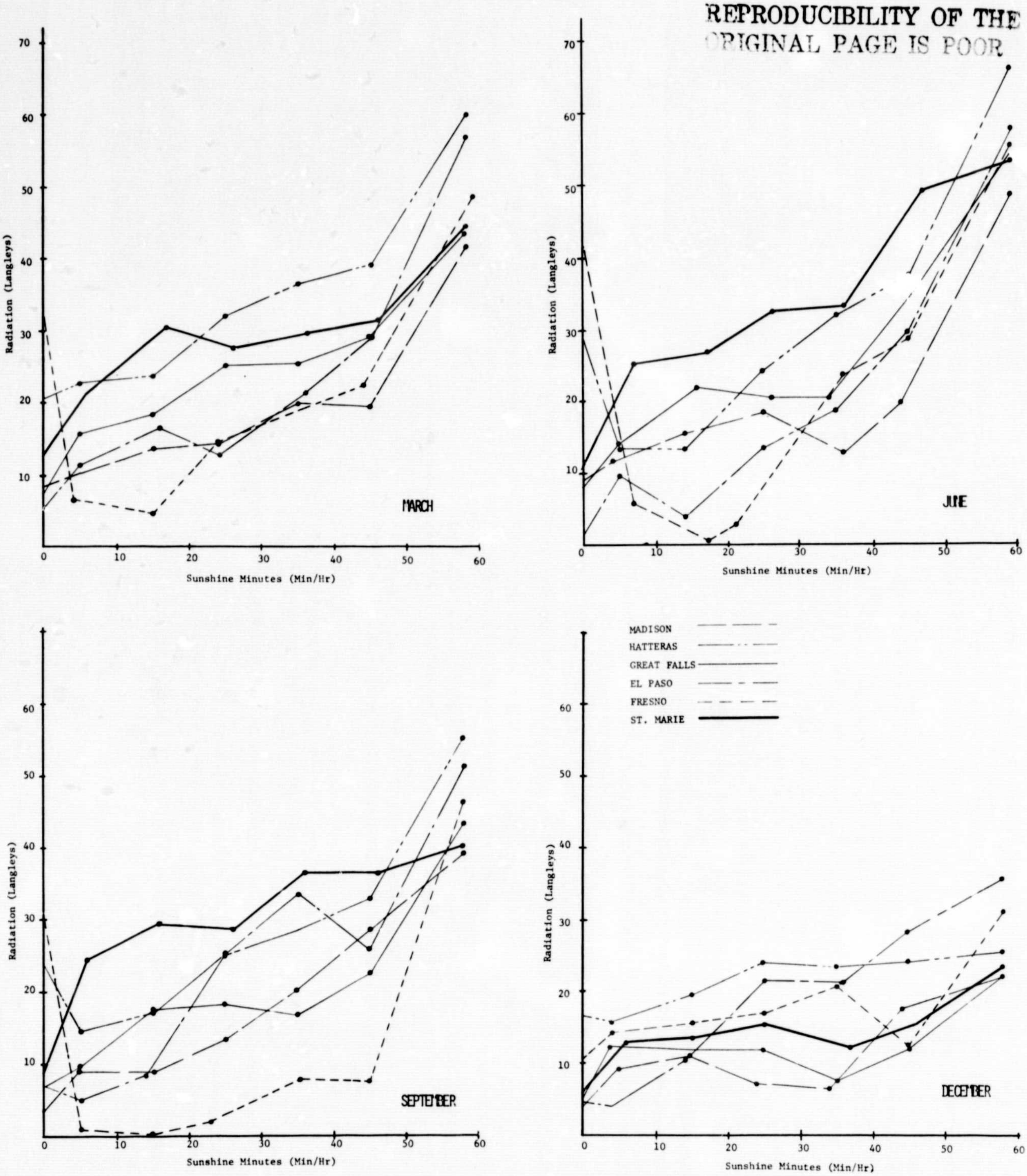


FIG. 8 RADIATION VS. SUNSHINE FOR FOUR SOLAR MONTHS (5-YEAR AVERAGES, 6 STATIONS)

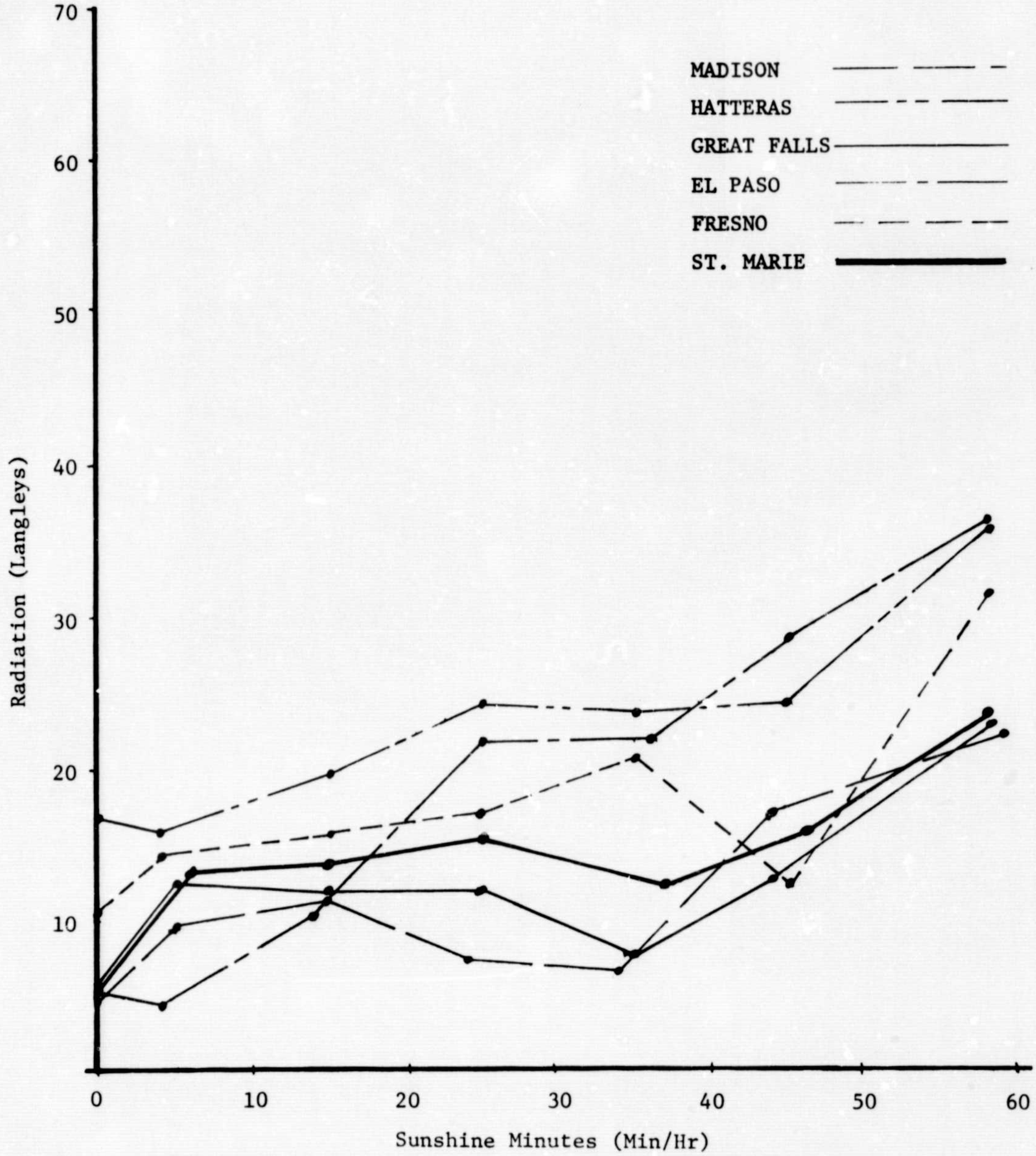


FIG. 9 RADIATION VS. SUNSHINE, ANNUAL CURVES (5-YEAR AVERAGES, 6 STATIONS)

statistics one would expect to compile from the visual satellite data in a study such as this. They are also available in other forms (i.e., hourly airways observations) from an order of magnitude greater number of stations than the other types of data, a factor which will become more important as the satellite data are computer-reduced for the many thousands of points we propose and one must look for a far greater number of ground truth observations to cover specific situations than would be available for "radiation" data alone.

3.0 SUNSHINE/CLOUD DATA FROM GEOSTATIONARY CLOUD IMAGES

3.1 Satellite Data Sources

Daytime satellite imagery from the Stationary Meteorological Satellite or Geostationary Operational Environmental Satellite (SMS/GOES) located at 75° West longitude over the equator has been used to provide cloud/sunshine data for 1975. These data are from the .55 - .75 micrometer visual channel. Three of the planned international global network of five GOES are now in operation. The first is at 75° West, the second at 135° West, and the third launched in the summer of 1977 for the Japanese is at 140° East over the equator. The last two are to be placed in operation in 1978 at 70° East by the USSR and at 0° by the European nations. Figure 10 shows the approximate locations and coverage of two of these satellites. This network will ultimately permit our satellite solar energy monitoring technique to be applied from about 60° North to 60° South on a worldwide basis.

The SMS/GOES satellites spin at 100 revolutions per minute. A Visible/Infrared Spin-Scan Radiometer (VISSR) has a scanning mirror that faces the earth for about one-twentieth of each complete 360-degree rotation, scanning west to east in eight identical visible channels and two redundant IR channels. The scan data that we use from the satellite at 75° West longitude, is immediately transmitted in digital form to the Wallops Island, Virginia, Command and Data Acquisition station (CDA). While the spacecraft is completing its revolution, the mirror moves to the next southward step and scans again when it is looking at the earth once more.

Within 18.2 minutes, the radiometer accomplishes the 1821 scan steps required to provide an image of the coverage area, Figure 10. The resulting visible images, made only in daylight, contain 14,568 lines, and have a resolution of one kilometer at the satellite sub point which is at the equator. IR images, acquired in darkness as well as in daylight, have a total of 1821 lines, with approximately 8 kilometers resolution at the sub point. Allowing time for the scanning mirror to return to its starting point, and for correction of any "wobble" which may be caused by this rotating action, the picture

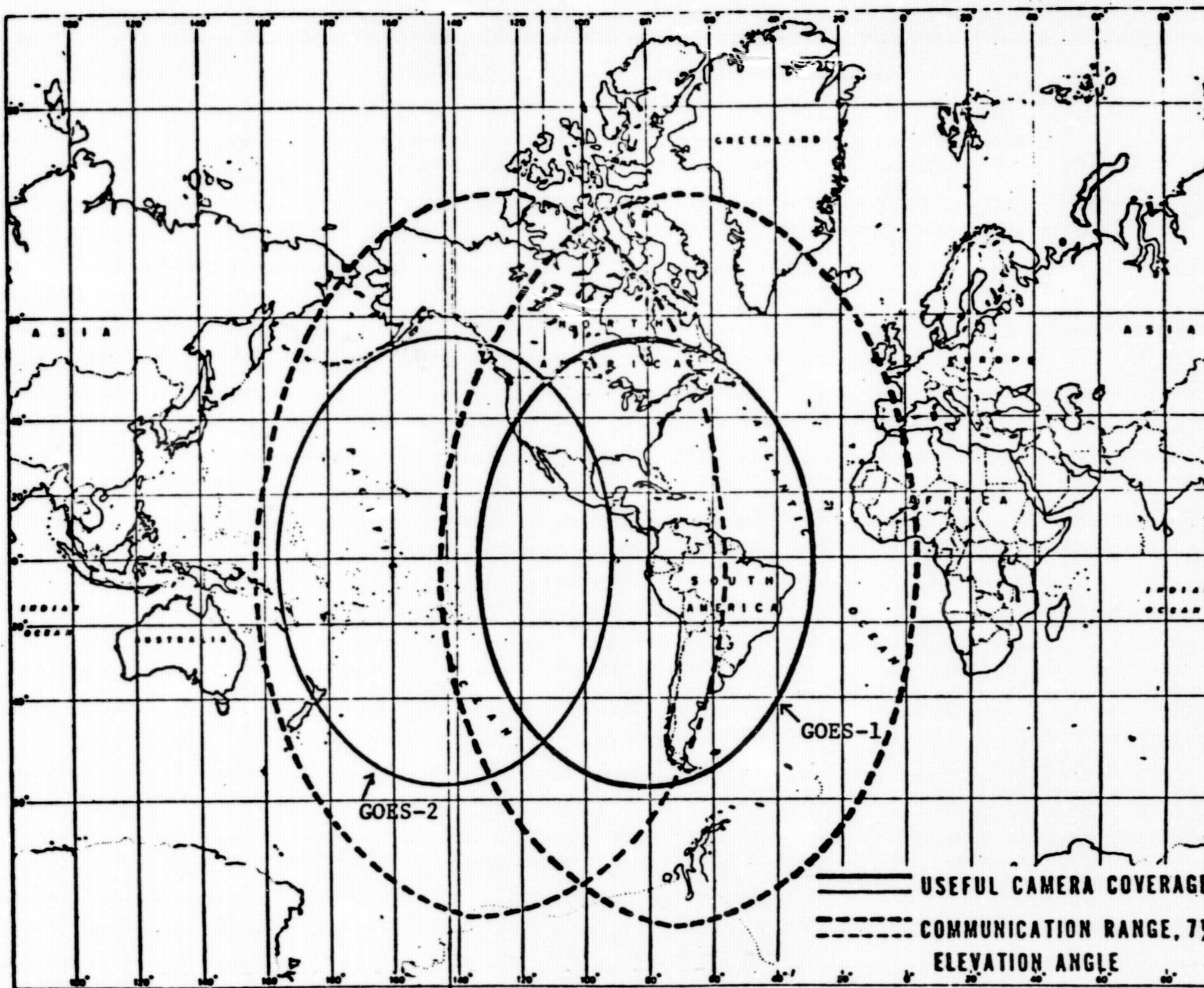


Figure 10. Typical coverage from a 2-GOES system showing area of useful camera coverage and communications range at 7.5-degree antenna elevation for data collection and relay.

coverage is scheduled at 30-minute intervals. That picture rate provides more data each day than is necessary for our studies.

At the CDA station, the eight lines of visible data acquired while the spacecraft looks earthward are gridded automatically and the rate of data transmission reduced, "stretched." As the satellite is completing its revolution and the VISSR is looking toward space, the stretched visible data signals are retransmitted from the CDA station through the satellite to the National Environmental Satellite Service (NESS) at Federal Office Building Number 4 in Suitland, Maryland, and then relayed by microwave to the NESS Central Facility a few miles away.

Unfortunately, the large number of digital data tapes generated by SMS/GOES is erased almost daily and reused. The archive data available to us from the NOAA/NESS in Suitland, Maryland, are in the form of 10 x 10 inch photo transparencies covering the USA and surrounding areas, Figure 11. This is known as the WB-1 sector, and it covers a larger geographical area than we require.

In the future, digital data should be acquired in real time for the geographic area desired from a "sectorizer" such as that at the University of Wisconsin. Their sectorizer will provide a 2000 x 2000 matrix of digital data for any selected portion of the full disk image viewed by an SMS/GOES satellite. This was not available in time for use on our project. The WB-1 sector photo transparencies are more difficult to redigitize and computer process, but they served our purpose to develop the technique for solar energy monitoring by geostationary satellites.

3.2 Satellite Data Analysis

Portions, such as those marked in Figure 11, of the analog grey scale 10 x 10 inch photo transparencies acquired from NOAA/NESS were read on the television scanner of a GE Image-100 at the NASA Kennedy Space Center. This scanner produces 512 digital bits of photo transmissivity data per line for 512 lines. The programmed output was a digital tape which we processed on the University of Miami Univac 1106 Computer. For our purposes, 512 pixels were used to cover the U.S.

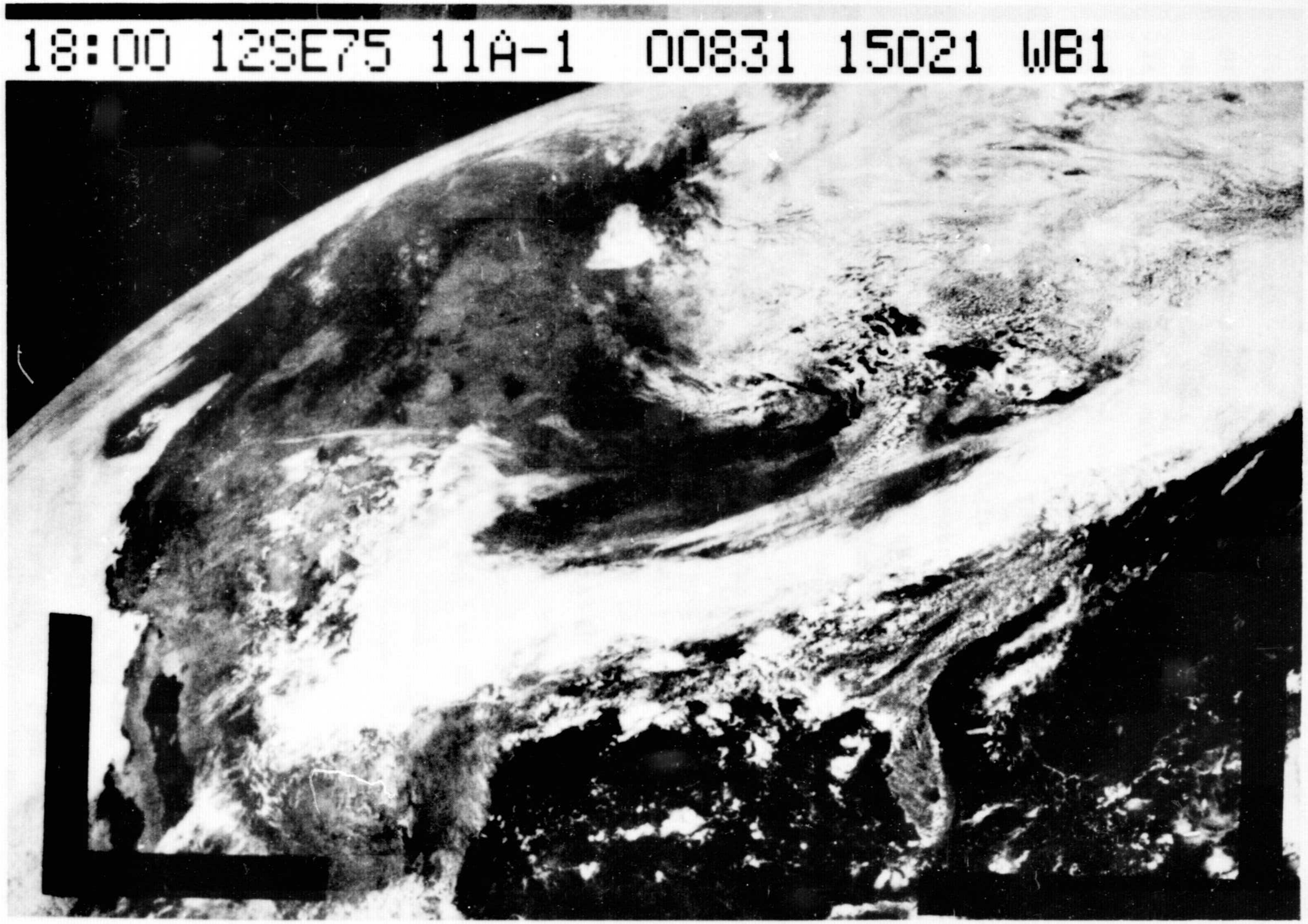


Fig. 11. WB-1 Sector of SMS/GOES Full-Disc Image. One-mile Resolution at Satellite subpoint on Equator. Tape marks east-west and south boundaries that we scanned with Image-100.

from west to east and approximately 250 pixels were adequate coverage from north to south. The remaining pixels of data did not have to be processed. Two thousand pixels of input data east-west by one thousand pixels north-south would be better for analysis purposes because it would allow some space averaging of the data to remove noise and still provide better resolution than at present.

The General Electric Image-100 read the photo transparencies to 64 levels of transmissivity. These were printed out to 32 levels on the Univac 1106 computer. Single digits 0 through 9 plus 22 letters of the alphabet were used to represent these 32 levels so that each pixel contained only one character on the printout. Since the transparencies were positives, the largest transmissivity values were opaque clouds with a high albedo; and the lowest values were water, with the next to lowest values from land. The absolute values vary with satellite viewing angle and change with time of day or sun angle. Corrections for these are discussed later.

The WB-1 sector transparencies that we used had a resolution of one nautical mile at the subpoint. This is degraded, due to viewing angle, about 18% at Miami to 1.18 nautical miles and to about 4.0 miles at the far corner of the photograph near Seattle, Washington. The Image-100 pixels of redigitized data have a resolution of approximately 4 nautical miles in southern Florida and 7 nautical miles in the state of Washington. Thus each digit on our computer generated maps represents the average reflectance value for approximately 9 original satellite pixels in south Florida and 4 pixels near Seattle, Washington.

3.2.1 Satellite Data Normalization

Three types of corrections were considered in order to normalize the satellite data so that the transmissivity values in the pixels could be used to identify water, land, thin clouds, and dense or opaque clouds. One was for errors introduced by the optical scanner of the Image-100 used to redigitize the photo transparencies. Another was for satellite viewing angle and the third was for time of day or sun angle.

Inhomogeneties in the light table and other non-linearities of the General Electric Image-100 optical scanner introduced a known

pattern of errors in the output digitized cloud/sunshine maps. An approximate correction for these errors was prepared by reading a low density homogeneous film on the Image-100 and recording the non-uniform transmissivity values that were read out. Figure 12 shows the magnitude and spatial distribution of these errors on a scale of 64 levels of transmissivity. The values in this figure are averages for 18 x 18 pixel squares. A computer program was written to subtract these values from the basic data before the cloud/sunshine maps were printed.

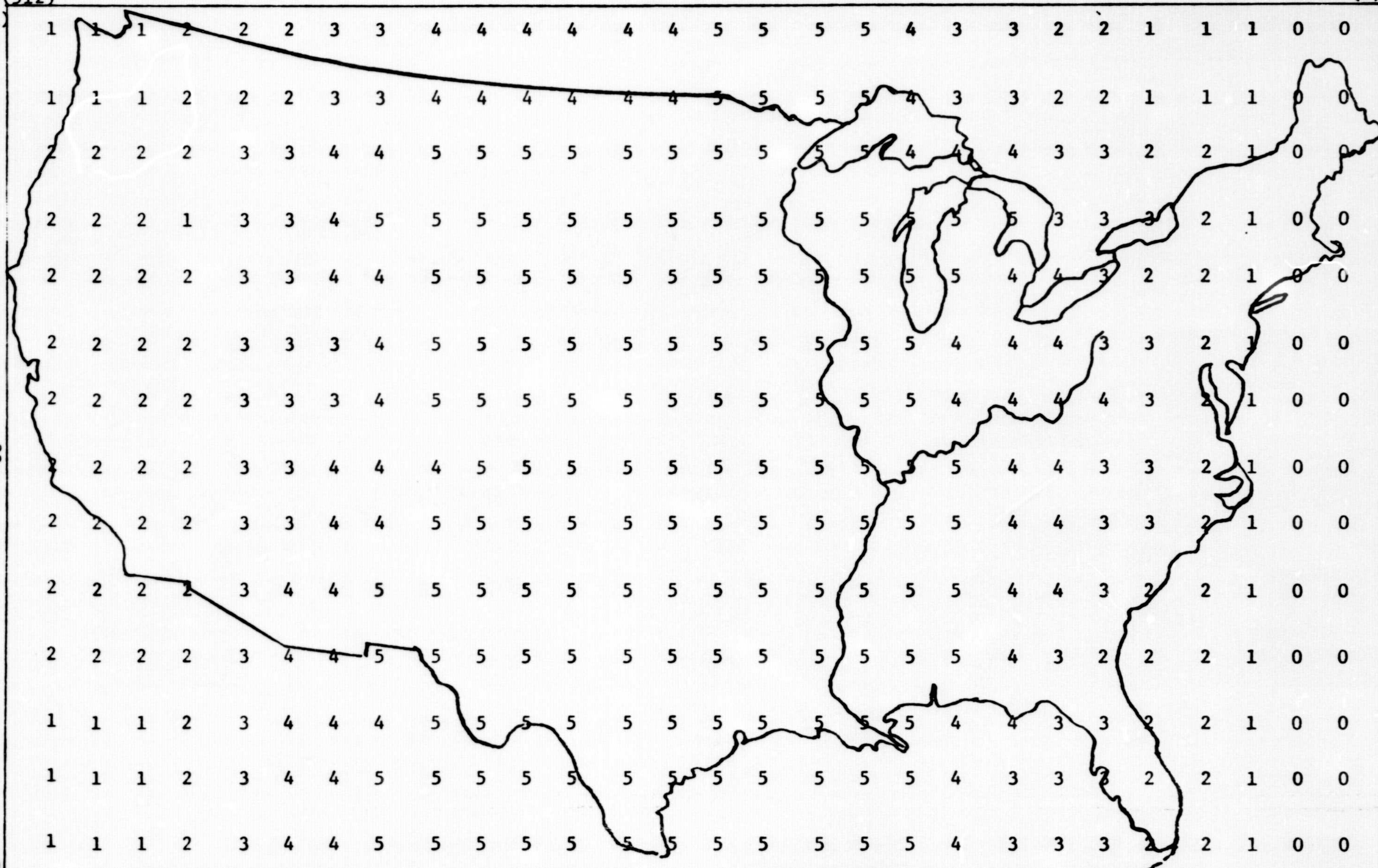
Our geographic area of investigation encompassed approximately 504 pixels east-west and 252 pixels north-south. This covers from the Canadian border to the Florida Keys and from Maine to California as shown in Figure 12. The first 8 to 10 pixels of each scan line of the Image-100 are not useable data. We scanned the images in an inverted manner, starting with Florida, so that most of these unuseable pixels are off the Atlantic coast, except possibly the eastern tip of Maine.

3.2.2 Satellite Viewing Angle and Sun Angle Correction

The correction of reflectivity measurements for sun angle is much larger and thus more important than the correction for satellite viewing angle. One reason for this is that the geographic area viewed by a unit area of the camera lens increases as the viewing angle increases. The increase in light gathering area helps to offset the oblique angle decrease in light intensity. This is related to the space scale resolution of the satellite which is also a function of the viewing angle.

Another reason for the much greater significance of the sun angle correction is the magnitude of the solar zenith angles. During the most productive portion of the solar insolation day in winter in the northern United States, they range from about 70 to over 80 degrees and during that season in the southern part of the country they range from approximately 50 to 75 degrees. The difference in satellite viewing angle from the nearest point, south Florida, to the farthest point, in the state of Washington is only seven degrees.

Theoretically, the correction for sun angle, or subject illumination, is a function of the cosine of the solar zenith angle. We can normalize the data in any particular image to a point on the earth where



1	1	1	2	2	2	3	3	4	4	4	4	4	4	5	5	5	5	4	3	3	2	2	1	1	1	0	0
1	1	1	2	2	2	3	3	4	4	4	4	4	4	5	5	5	5	4	3	3	2	2	1	1	1	0	0
2	2	2	2	3	3	4	4	5	5	5	5	5	5	5	5	5	5	4	4	4	3	3	2	2	1	0	0
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1	1	1	2	3	4	4	4	5	5	5	5	5	5	5	5	5	5	5	4	4	3	3	2	2	1	0	0
1	1	1	2	3	4	4	5	5	5	5	5	5	5	5	5	5	5	5	4	3	3	3	2	2	1	0	0
1	1	1	2	3	4	4	5	5	5	5	5	5	5	5	5	5	5	5	4	3	3	3	2	2	1	0	0

Fig. 12 TABLE OF NEGATIVE CORRECTIONS TO SATELLITE DATA FOR GE IMAGE-100 ERRORS
(Each number is average correction for 18 x 18 pixels.)

the solar zenith angle was zero at the time of the image simply by dividing the reflectivity values at all other points by the cosines of their respective solar zenith angles. This leaves the value unchanged at the point where the solar zenith angle is zero and increases all other values as the solar angle increases. We applied this sun angle correction and disregarded the smaller satellite viewing angle correction.

A three by seven grid was prepared for the satellite view of the United States, Figure 13, and the cosine of the solar zenith angle was computed for the center point of each of the grid squares. A computer lookup table was prepared, Table 3. Then, each reflectivity measurement that fell within a particular grid was divided by the cosine of the solar zenith angle for that grid square before the numerical map printout was made. Figure 14 is an example of the corrected computer printout of cloud cover.

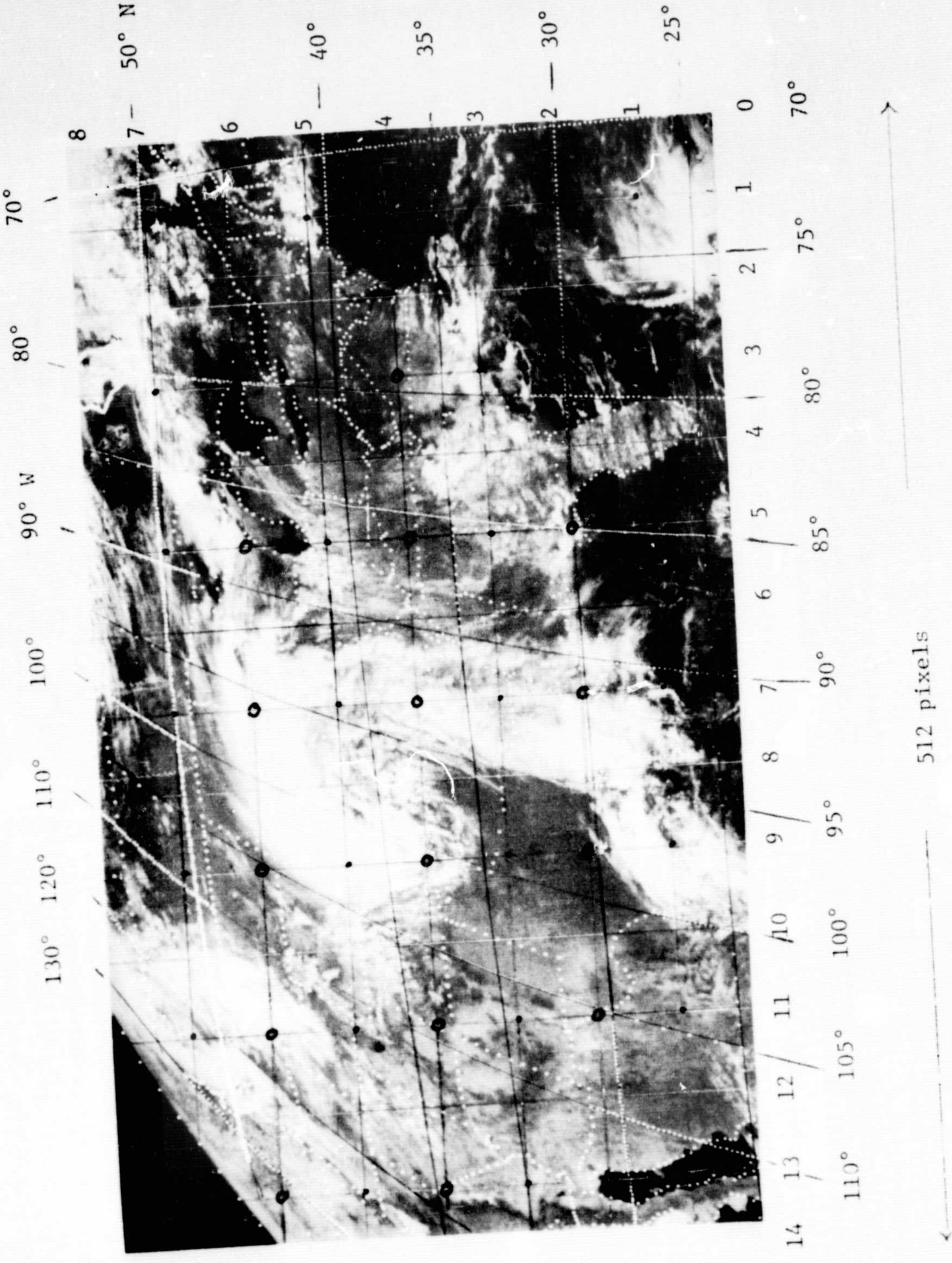

Figure 13. Grid for GE Image-100 GOES Image.

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Fig. 14 Corrected Computer Printout of Cloud Cover

Table 3 SOLAR ZENITH ANGLE CORRECTIONS (COSINE Z) FOR SMS/GOES SATELLITE IMAGE AT 1800 GMT

# of Grid	Grid	Long.	Lat.	Local-Mean Solar Time	a Altitude	z Zenith	Cos z
1	(1,2)	72.86	30.00	13:14'	60	30	0.87
2	(3,2)	78.93	30.00	12:46'	63	27	0.89
3	(5,2)	85.00	30.00	12:24'	64	26	0.90
4	(7,2)	91.50	30.50	11:58'	65	25	0.91
5	(9,2)	97.78	30.60	11:32'	64	26	0.90
6	(11,2)	105.50	30.74	11:00'	62	28	0.88
7	(13,2)	113.30	31.00	10:32'	58	32	0.85
8	(1,4)	72.60	37.21	13:13'	55	35	0.82
9	(3,4)	79.34	37.20	12:46'	56	34	0.83
10	(5,4)	86.11	37.20	12:20'	57	33	0.84
11	(7,4)	93.16	37.50	11:52'	56	34	0.83
12	(9,4)	100.67	38.00	11:24'	54	36	0.81
13	(11,4)	109.31	38.33	10:46'	52	38	0.79
14	(13,4)	118.52	39.46	10:12'	48	42	0.74
15	(1,6)	72.35	45.52	13:14'	48	42	0.74
16	(3,6)	80.50	45.71	12:42'	49	41	0.75
17	(5,6)	88.13	45.86	12:12'	50	40	0.77
18	(7,6)	96.07	46.21	11:40'	49	41	0.75
19	(9,6)	105.50	46.55	11:00'	45	45	0.71
20	(11,6)	113.33	47.59	10:32'	43	47	0.68
21	(13,6)	--	--	--	--	--	--

- All angles in decimal degrees.
- Data from Smithsonian Tables (1957).
- Sept. 13 δ (declination) = + 4° 6'.
- 18:00 Z Greenwitch - Subtract 4 minutes for each degree to the West.
- Eq. of time added to local standard to obtain local mean solar time = + 3' 45".

4.0 CONVERTING SATELLITE CLOUD DATA TO EQUIVALENT SOLAR RADIATION

The ultimate use of the computer generated cloud/sunshine maps is to depict the mesoscale distribution of solar energy as a function of season of the year and time of day. Figures 15 and 16 illustrate this link. Figure 15 gives the relations between sky cover and solar radiation for two midday hours at six stations for the four seasons. The end points of each curve generally have the highest statistical significance because they have the largest number of observations. For practical purposes, each of the curves can be smoothed to resemble the hypothetical curves for the four seasons in Figure 17.

One might expect the March and September equinox curves to be identical. But more turbulent mixing and less haze on clear days in March appears to give a slightly higher average radiation at all stations than in September.

Figure 16 is similar to Figure 15 except that the combined hours are for morning and afternoon comprising approximately equal sun angles on each side of solar noon at the respective stations and seasons. Since the satellite produces cloud images every half hour, it is possible to computer tabulate the average sky cover by hours of the day for each month or for the four seasons. After smoothing the curves in Figures 15 and 16 to approximately resemble those in Figure 17, computer lookup values of radiation for a given satellite reflectance can be obtained from them.

In our study, satellite reflectance values less than 38 represented clear skies during midday hours, and values greater than 53 represented opaque overcast skies. These reflectance values and the corresponding opaque sky cover are shown at the top and bottom of Figure 17. By use of these relationships, opaque sky cover for a given hour or the monthly or seasonal mean for that hour, as determined by satellite, can be converted to equivalent global radiation received at the earth's surface. The final computer printout can be in Langleys per hour or watts per square meter, etc.

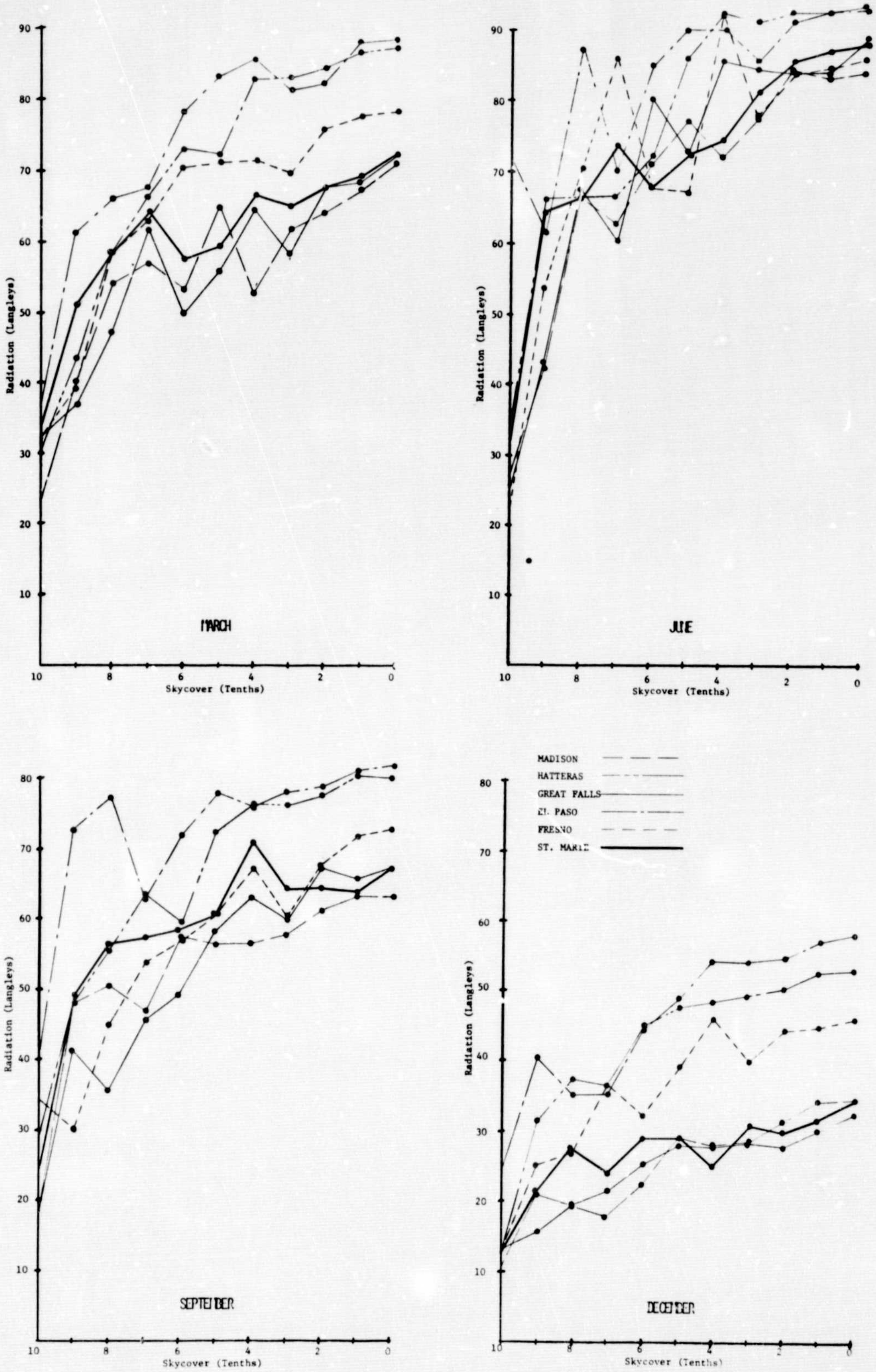

FIG. 15 RADIATION VS. SKYCOVER BY SEASONS FOR HOURS BEGINNING 1100 AND 1200 (5-YEAR AVERAGES, 6 STATIONS)

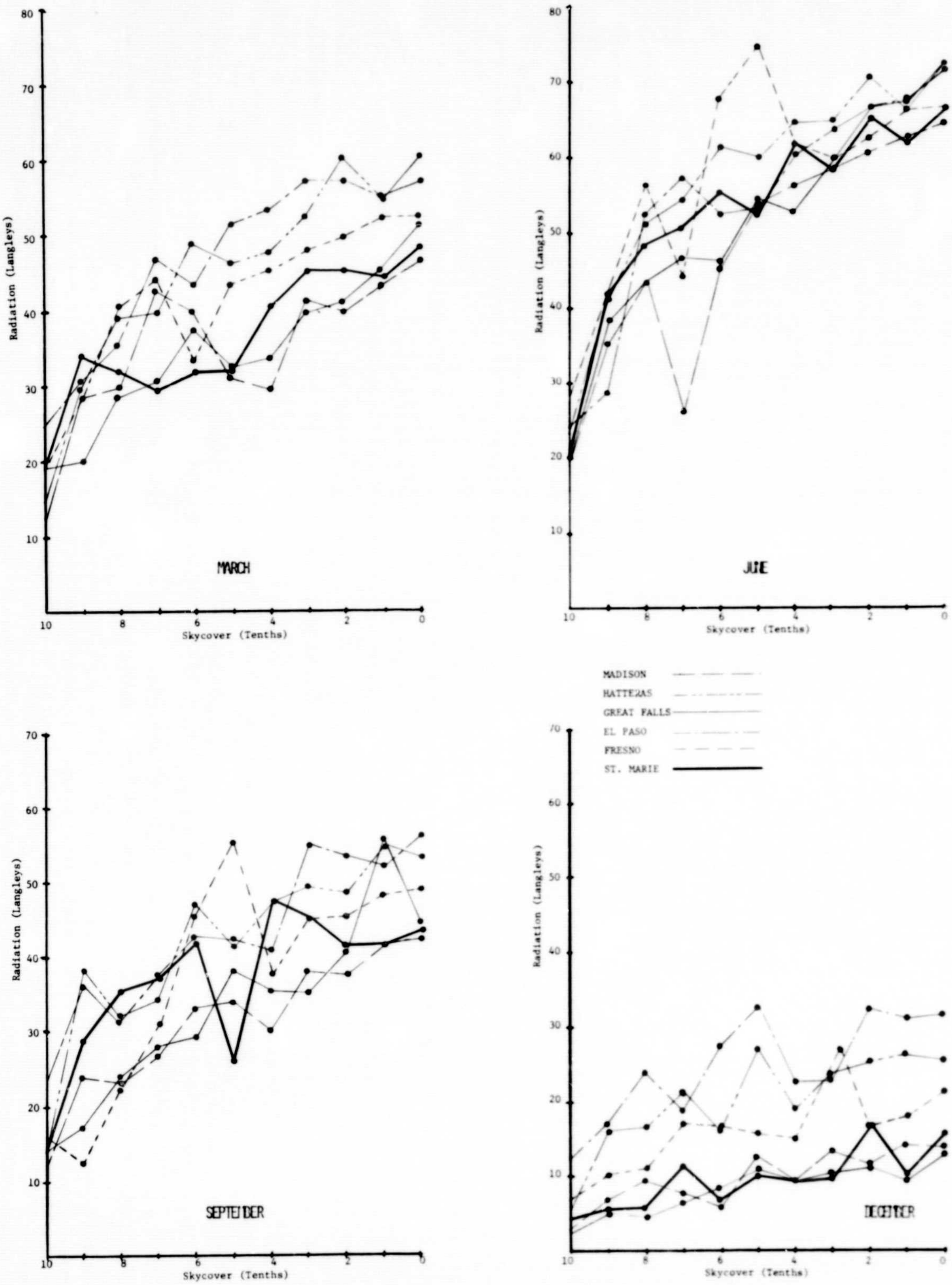

FIG. 16 RADIATION VS. SKYCOVER BY SEASONS FOR HOURS BEGINNING 0900 AND 1500 (5-YEAR AVERAGES, 6 STATIONS)

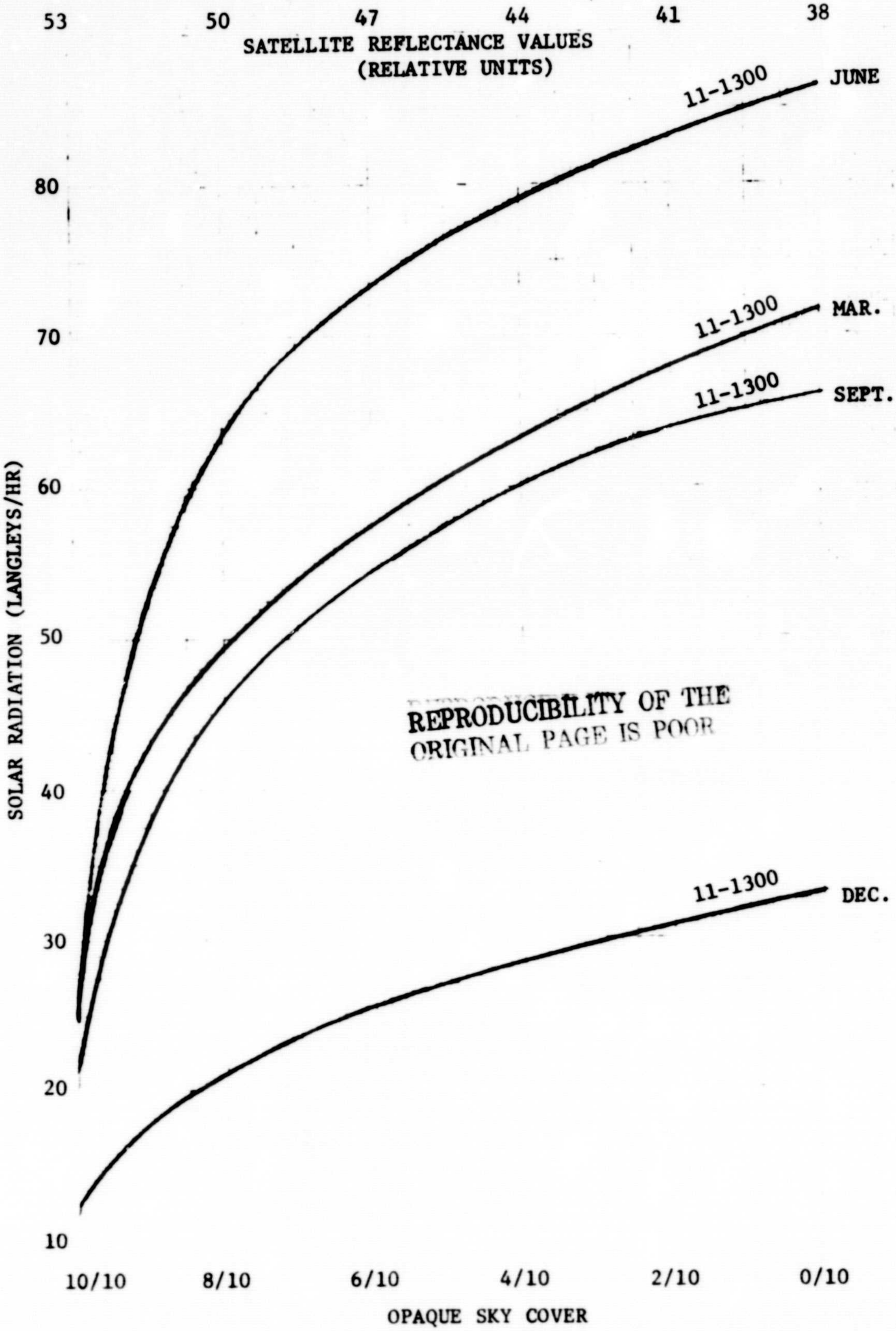

Fig. 17 Solar Radiation vs. Opaque Sky Cover and Satellite Observed Reflectance for Midlatitude Stations Near Noontime.

The September midday curve in Figure 17 can be applied in the eastern United States to the 1800 GMT, 12 September 1975 computer printout of cloud cover in Figure 14. The stations for which hourly solar radiation data were available, in most cases, were either in the clear or under the large opaque cloud band extending southwestward from New England through the Ohio Valley to the Rocky mountains. Nashville, Tennessee under opaque clouds received 9.7 Langleys for the hour ending at 1300 TST. Columbia, Missouri, in the clear received 76.8 Langleys for the hour ending at 1200 TST. Dodge City, Kansas with cirrus clouds on the north side of the major cloud belt received 71.4 Langleys. Madison, Wisconsin in the clear received 73.2 Langleys. Bismarck, North Dakota, under cirrus clouds received 60.0 Langleys. Cape Hatteras, North Carolina, with scattered to broken clouds received 66.2 Langleys for the hour ending at 1300 TST and Caribou, Maine, under the opaque cloud band received 6.1 Langleys.

These results indicate either that the model needs to be fine tuned for station latitude or that the variations from the mean in solar radiation are greater for some stations than for others. For instance, Madison radiation under opaque sky cover is less than both Great Falls, Montana, and Sault Ste. Marie, Michigan, in March and December and lower than Sault Ste. Marie, Michigan in September, despite its more southerly latitude.

Also, there was a tendency to overestimate the radiation under opaque overcast conditions. This may have been due to rain along with the opaque cloud cover at some stations. Rain would further reduce the incoming radiation below that for opaque clouds alone. However, an overestimate under these conditions is not serious since it is on the low unproductive end of the scale. A large, high-gain collector would be necessary to utilize the low radiation under opaque sky conditions.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Data should be obtained on tape, properly navigated in essentially real time as accomplished with the University of Wisconsin system [22]. It is then far more convenient to correlate the ground station observations of minutes of sunshine, cloudiness, and global energy for a given period with the satellite observations. In addition, many localities are now monitoring air quality on an hourly or daily basis so that this important variable can also be used to improve the correlations between the actual energy measured at the earth's surface and what can be inferred from the satellite observations.

ERTS-1 satellite photographs have been used (University of Wisconsin, [23]) to show smoke plumes which were several kilometers wide and several hundred kilometers long downwind of large industrial complexes. Probably most of the NOAA sunshine, cloudiness and pyranometer observations would completely overlook such plumes which could be very important considerations in the placement of potential solar power sites. With westerly winds prevailing over the northern and eastern 1/3 of the United States, one would expect to use relatively simple climatology to good effect. However, important meso-meteorological variations are completely missing from such climatological summaries due to instrument location and growth of urban and industrial complexes at various locations with respect to the instrument sites; and pollution sources other than those easily identifiable can provide plentifully dirty air which escapes the site study. Even where all such modifying influences can be identified, much effort (sometimes with inaccurate or fruitless results) must be expended to determine their theoretical effects on the environment. Certainly it would be better to assess the effects empirically, if possible. Use of satellite data by methods outlined above is the only way all such effects can be studied and determined.

Computer generated mean cloud/sunshine maps by hours of the day and seasons of the year can ultimately be converted to equivalent solar radiation at the earth's surface by use of techniques outlined in Section 4.0. This will permit high-resolution interpolation and extrapolation in areas where no radiometer measurements are available.

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